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DOUBLE-DETONATION EXPLOSIONS AS PROGENITORS OF TYPE IAX SUPERNOVAE

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ABSTRACT

It has recently been proposed that one sub-class of type Ia supernovae (SNe Ia) is sufficiently both distinct and common to be classified separately from the bulk of SNe Ia, with a suggested class name of "type Iax supernovae" (SNe Iax), after SN 2002cx. We show that the population properties of this class can be understood if the events originate from helium double-detonation sub-Chandrasekhar mass explosions, in which a carbon–oxygen white dwarf (CO WD) accumulates a helium layer from a non-degenerate helium star. We have incorporated detailed binary evolution calculations for the progenitor systems into a binary population synthesis model to obtain birthrates and delay times for such events. The predicted Galactic event rate is $\sim 0.6 - 1.8 \times 10^{-3}\,\mathrm{yr}^{-1}$, in good agreement with the measured rates of SNe Iax. In addition, predicted delay times are $\sim 70\,\mathrm{Myr} - 710\,\mathrm{Myr}$, consistent with the fact that SNe Iax have so far only been discovered in late-type galaxies. Based on the CO WD mass at explosion and previous detonation models, we also estimate the distribution of resulting SN brightness ($-13 \gtrsim M_{\mathrm{bol}} \gtrsim -19$ mag), which can reproduce the empirical diversity of SNe Iax. We speculate on why binaries with non-degenerate donor stars might lead to SNe Iax if similar systems with degenerate donors do not and suggest that the higher mass of the helium layer necessary for ignition at the lower accretion rates typically delivered from non-degenerate donors might provide the explanation.

Subject headings: binaries: close — stars: evolution — supernovae: general

1. INTRODUCTION

Type Iax supernovae (SNe Iax) have been proposed to form a distinct sub-class of sub-luminous SNe Ia, containing SNe resembling the prototype event SN 2002cx (Li et al. 2003; Foley et al. 2012). Those SNe Iax are spectroscopically similar to SNe Ia, but have lower maximum-light velocities ($2000 \lesssim |v| \lesssim 8000\,\mathrm{km\,s^{-1}}$), typically lower peak magnitudes ($-14.2 \gtrsim M_{\mathrm{V}} \gtrsim -18.9$ mag),[4] and maximum-light spectra that typically resemble those of the bright 1991T-like events. Since the estimated rate of SN Iax is roughly one third of the SN Ia rate, they are relatively common astrophysical events, although only 25 members of the class are currently identified (Foley et al. 2012).

SNe Iax appear not to obey the standard luminosity-width relation of SNe Ia (Foley et al. 2012 and references therein); clearly this would affect any use of them as distance indicators. However, perhaps more importantly, this behaviour of SNe Iax also gives us an opportunity to help us understand the physics of thermonuclear supernovae in general, since whatever mechanism produces SNe Iax leads to an alternative family of lightcurve shapes from standard SNe Ia. Deducing the progenitors of these explosions should help us to understand how this family of explosions differs from standard SNe Ia. Observations support the supposition that SNe Iax are from thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs), due to the evidence of C/O burning in their maximum-light spectra (Foley et al. 2012). SNe Ia lack helium in their spectra, yet two SNe Iax do show strong helium lines in their spectra, and so there must be helium in their progenitor systems. However, there is no hydrogen in any SN Iax spectra, and significantly less hydrogen than helium is typically required to cause a signature in an SN spectra (see, e.g., Hachinger et al. 2012). That spectral evidence suggests that in the SN Iax progenitor systems a CO WD is accreting from a non-degenerate helium star or a He WD. Of those, the CO WD + He WD systems would exist in old stellar populations, which is inconsistent with the observation that so far SNe Iax have exclusively been discovered in late-type galaxies (e.g., Valenti et al. 2009; Foley et al. 2012). However, CO WD + He star systems are expected primarily in young stellar populations, as has been observed. In this Letter, we investigate the population properties of CO WD + He star systems and ask whether they are consistent with being the progenitors of SNe Iax.

A CO WD can accrete material from a helium star to increase its mass until it ignites near to the Chandrasekhar mass limit (e.g., Wang et al. 2009a). However, standard Chandrasekhar mass explosion models have difficulty in reproducing the low luminosities of SNe Iax (Hillebrandt & Niemeyer 2000). It is therefore natural to consider whether SNe Iax might be produced by sub-Chandrasekhar mass explosions, in which the explosion of a CO WD is triggered by the detonation of a substantial surface layer of accreted helium (see, e.g., Nomoto 1982; Woosley et al. 1986). However, the details of what happens following burning of the helium layer are still unclear. If helium ignites at the bottom of the helium layer, this may result in an event known as helium

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[4] A typical peak brightness of normal SNe Ia is about −19 mag, and with a spread in brightness of ∼1 mag (e.g., Benetti et al. 2005).

double-detonation, during which one detonation wave propagates outward through the helium layer, whereas an inward propagating pressure wave compresses the CO core and leads to ignition followed by an outward detonation (see, e.g., Livne 1990; Woosley & Weaver 1994). Helium double-detonation sub-Chandrasekhar mass explosions have previously been considered as promising explanations for standard SNe Ia (see, e.g., Branch et al. 1995; Höflich & Khokhlov 1996), but modern models disagree over which known SNe, if any, such systems might produce (see, e.g., Fink et al. 2007, 2010; Kromer et al. 2010; Woosley & Kasen 2011).

There are numerous complications, including that the properties of the helium layer that lead to helium ignition itself are expected to be a function of CO WD mass and accretion rate (see, e.g., Bildsten et al. 2007; Shen & Bildsten 2009). Heating from differential rotation in the accreted layer provides further uncertainty (Yoon & Langer 2004). Transients have also been observed which are consistent with the detonation of a thick helium layer on a WD which does *not* lead to a double-detonation (Poznanski et al. 2010; Kasliwal et al. 2010). Previous studies have often made the simplification that, for sufficiently massive CO WDs, a helium layer with mass $0.1\,M_{\odot}$ can ignite and lead to a double detonation (e.g., Ivanova & Taam 2004; Ruiter et al. 2011), and Fink et al. (2007, 2010) support the position that layers of that mass can produce a double-detonation.

Generic double-detonation scenarios have previously been suggested for SNe Iax, but inconclusively (see, e.g., Foley et al. 2012 and references therein). We note that Foley et al. (2009) suggested that an alternative explosion model might be responsible for SNe Iax, specifically a failed deflagration model (see, e.g., Foley et al. 2012). In models like this, the accreting WD would survive and potentially possess peculiar observational properties (see also Jordan et al. 2012; Kromer et al. 2012).

Overall, determining the progenitors of SNe Iax could distinguish between theoretical models which are largely separated by precise details of thermonuclear explosion physics at WD densities.

In §2 we further describe our assumptions and binary evolution calculations. Our population synthesis results are presented in §3, followed by a discussion and summary in §4.

2. BINARY EVOLUTION CALCULATIONS

Employing Eggleton's stellar evolution code (Eggleton 1973; later updated by Han et al. 1994; Pols et al. 1998), we have calculated the evolution of the CO WD + He star systems. Roche lobe overflow (RLOF) is treated within the code as described by Han et al. (2000). We set the ratio of mixing length to local pressure scale height, $\alpha = l/H_{\rm p}$, to be 2.0. In our calculations, the initial helium star models are composed of helium abundance $Y = 0.98$ and metallicity $Z = 0.02$. Orbital angular momentum loss due to gravitational wave radiation (GWR) is included.

In the double-detonation model, the helium star transfers some of its material onto the surface of the WD, which increases the mass of the WD as a consequence. If the mass-transfer rate onto the WD from the helium star is higher than $4\times10^{-8}\,M_{\odot}\,{\rm yr}^{-1}$, stable burning allows the CO mass of the WD to increase (Woosley et al. 1986; see also Wang et al. 2009a and references therein). For lower accretion rates ($1\times10^{-9}\,M_{\odot}{\rm yr}^{-1} \lesssim |\dot{M}_2| \lesssim 4\times10^{-8}\,M_{\odot}{\rm yr}^{-1}$), a thick layer of helium is believed to grow on the surface of the WD. When the mass-transfer rate drops even further ($|\dot{M}_2| < 1\times10^{-9}\,M_{\odot}{\rm yr}^{-1}$), the flash when the helium layer ignites has been suggested to be too weak to initiate a carbon detonation, which results in only a single helium detonation wave propagating outward (see, e.g., Nomoto et al. 1982).[5] For accretion rates of a few times $10^{-8}\,M_{\odot}{\rm yr}^{-1}$, Yoon & Langer (2004) have argued that heating by frictional dissipation significantly reduces the eventual chance of a helium detonation, leading to some uncertainty in these mass-transfer rate boundaries.

According to recent hydrodynamic simulations, the minimum WD mass for carbon burning might be $\sim0.8\,M_{\odot}$, since the detonation of the CO WD may be not triggered for lower mass (e.g., Sim et al. 2012). We also expect that the initial CO WD masses are below $\approx1.1\,M_{\odot}$ as more massive WDs – at formation – usually consist of oxygen and neon (i.e., ONe WDs). In principle, the WD could increase its CO mass by accreting helium as long as the mass-transfer rate is higher than $4\times10^{-8}\,M_{\odot}\,{\rm yr}^{-1}$, but this rarely occurs in our calculations (only helium donors with masses above $\approx1.1\,M_{\odot}$ lead to an increase in CO mass). Following the previous work described in the introduction, we assume that a double-detonation occurs when a helium layer with mass $0.1\,M_{\odot}$ accumulates on the surface of the WD.

We incorporated the prescriptions above into Eggleton's stellar evolution code and followed the evolution of an ensemble of CO WD + He star systems. The mass lost from these systems is assumed to take away the specific orbital angular momentum of the accreting WD. We have calculated the evolution of about 600 WD + He star systems, thereby obtaining a large, dense model grid. The initial mass of the helium donor stars, $M_2^{\rm i}$, ranges from $0.3\,M_{\odot}$ to $1.3\,M_{\odot}$; the initial mass of the CO WDs, $M_{\rm WD}^{\rm i}$, is from $0.8\,M_{\odot}$ to $1.10\,M_{\odot}$; the initial orbital period of the binary systems, $P^{\rm i}$, changes from the minimum value, at which a helium zero-age main-sequence (ZAMS) star would fill its Roche lobe, to $\sim0.2\,{\rm d}$, where the helium star fills its Roche lobe at the end of the helium MS.

In Figure 1, we present an example of binary evolution calculations for the double-detonation model. The left panel shows the mass-transfer rate and the mass of the WD envelope varying with time after the helium star fills its Roche lobe, whereas the right panel is the evolutionary track of the helium donor star in the Hertzsprung-Russell diagram, where the evolution of the orbital period is also shown. The WD + He star binary starts with ($M_2^{\rm i}$, $M_{\rm WD}^{\rm i}$, $\log(P^{\rm i}/{\rm day})$) = (0.60, 1.0, −1.4), where $M_2^{\rm i}$, $M_{\rm WD}^{\rm i}$ are the initial masses of the helium star and of the CO WD in solar mass, and the $P^{\rm i}$ is the initial orbital period in days. Due to the short initial orbital period (0.04 d), angular momentum loss induced by GWR

[5] Our upper accretion rate limit only directly affects a small fraction of our population. The lower limit is uncertain but might approximately be justified in an additional way, i.e., that below such rates the helium layer mass needed for ignition is too large to normally be reached (see, e.g., Shen & Bildsten 2009).

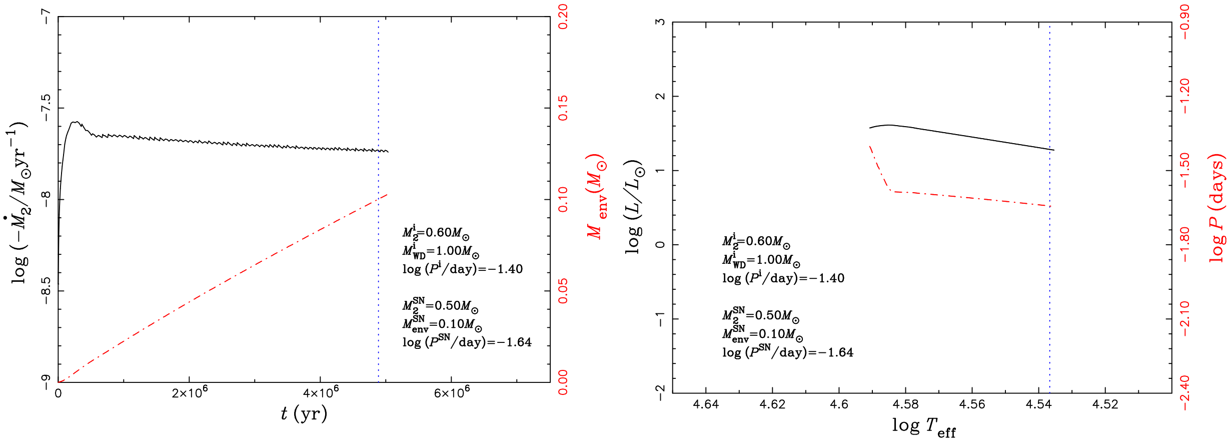

Figure 1. A representative example of binary evolution calculations. Left panel: the solid and dash-dotted curves show the mass-transfer rate and the mass of the helium layer on the WD varying with time after the helium star fills its Roche lobe, respectively. Right panel: the evolutionary track of the donor star is shown as a solid curve and the evolution of orbital period is shown as a dash-dotted curve. Dotted vertical lines in both panels indicate the position where the double-detonation may happen.

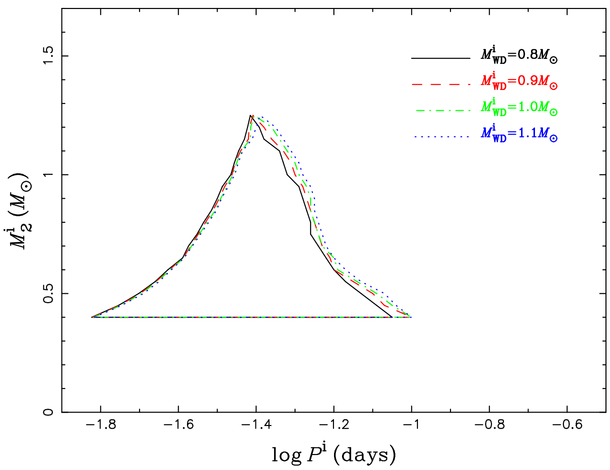

Figure 2. Regions in the initial orbital period–secondary mass plane (log P^{i}, M_2^{i}) for WD + He star binaries that produce SNe Ia for various initial WD masses.

is large, which leads to the rapid shrinking of the orbital separation. After about 11 million years, the helium star begins to fill its Roche lobe while it is still in the helium core-burning stage. The mass-transfer rate is stable and with a low rate of $\sim 2\times10^{-8}\,M_\odot\,\mathrm{yr}^{-1}$, which results in the formation of a helium layer on the surface of the CO WD. After about 5 million years, the mass of the helium layer increases to $0.1\,M_\odot$, at which point a detonation is assumed to occur at the base of the helium layer, and further assumed to produce a double-detonation explosion. At this moment, the mass of the helium star is $M_2^{\mathrm{SN}}=0.50\,M_\odot$ and the orbital period is $\log(P^{\mathrm{SN}}/\mathrm{day})=-1.64$.

Figure 2 shows the initial contours for producing SNe Ia in the $\log P^{\mathrm{i}} - M_2^{\mathrm{i}}$ plane for various WD masses, i.e., $M_{\mathrm{WD}}^{\mathrm{i}}=0.8$, 0.9, 1.0 and $1.1\,M_\odot$, where P^{i} and M_2^{i} are the initial orbital period and the initial mass of the helium donor star, respectively. From this figure, we can see that the contours are slightly shifted to higher periods with the increase of initial WD masses. This is because a helium star with a specific mass has a smaller Roche-lobe radius with a more massive WD companion. The left boundaries of the contours are set by the condition that RLOF starts when the secondary is on the helium ZAMS, whereas systems beyond the right boundary experience mass-transfer when the helium star evolves to the subgiant stage. The upper boundaries are set mainly by a high mass-transfer rate due to orbit decay induced by GWR and large mass-ratio, which makes the WD grow in mass to the Chandrasekhar mass limit (see Wang et al. 2009a). The lower boundaries are where the mass-transfer rate $\dot{M}_2$ is higher than $1\times10^{-9}\,M_\odot\mathrm{yr}^{-1}$ for just long enough to produce a $0.1\,M_\odot$ helium layer on the CO WD.

3. BINARY POPULATION SYNTHESIS

In this double-detonation model, the progenitor systems containing a CO WD + He star in a close binary have most likely emerged from the common-envelope (CE) evolution of a giant binary system. CE ejection is still an open problem. We use the standard energy equations to calculate the output of the CE phase (following Webbink 1984), in which there are two uncertain parameters, α_{ce} (the CE energetic ejection efficiency) and λ (a structure parameter that depends on the evolutionary stage of the donor star and the definition of the core-envelope boundary). As in previous studies (e.g., Wang et al. 2009b), we combine α_{ce} and λ into a single free parameter $\alpha_{\mathrm{ce}}\lambda$, and show results for two values: 0.5 and 1.5.

In order to obtain event rates and delay times for the double-detonation model, we performed a series of Monte Carlo BPS simulations. As initial conditions we assumed the initial mass function of Miller & Scalo (1979) and a constant initial mass-ratio distribution. The distribution of separations is also taken to be constant in $\log a$ for wide binaries, where a is the orbital separation, and the orbits are assumed to be circular. For each BPS realization we have used Hurley's rapid binary evolution code (Hurley et al. 2002) to follow the evolution of 10^7 sample binary systems from star formation to the formation of the CO WD + He star systems based on three evolutionary scenarios (i.e., the He star, EAGB and TPAGB channels; for details see Wang et al. 2009b). We then apply the calculations described in §2 and assume that if the initial parameters of a CO WD + He star system are located inside the relevant contour of Figure 2, a double-detonation explosion occurs.

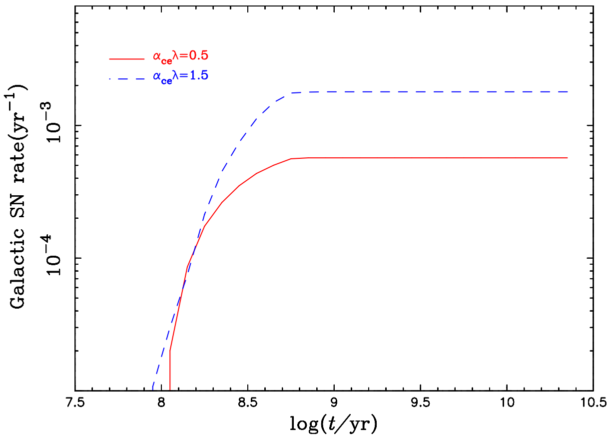

Figure 3. Evolution of Galactic SN Ia rates for a constant star-formation rate ($Z = 0.02$, SFR $= 5\,M_\odot \mathrm{yr}^{-1}$).

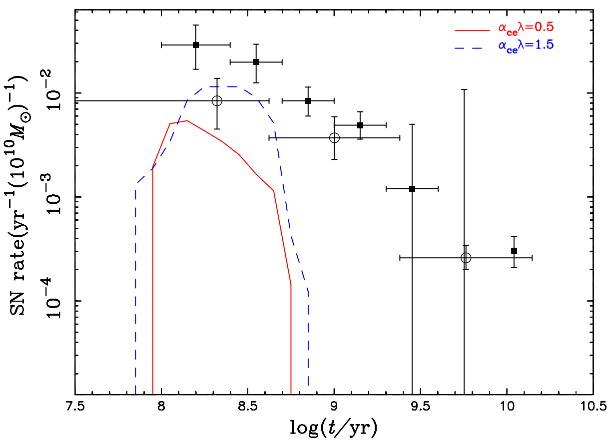

Figure 4. Delay time distributions of SNe Ia. The filled squares and open circles are taken from Totani et al. (2008) and Maoz et al. (2011), respectively.

3.1. *Rates and delay times*

We present results for a constant star-formation rate (SFR) – assumed to be constant for the past 14 Gyr – and also for a delta-function SFR, i.e., a single instantaneous starburst. In Figure 3, we show the evolution of Galactic SN Ia rates by adopting $Z = 0.02$ and SFR $= 5\,M_\odot\mathrm{yr}^{-1}$. This gives a Galactic event rate of $\sim 0.6 - 1.8 \times 10^{-3}\,\mathrm{yr}^{-1}$, which is roughly one third of the inferred Galactic SN Ia rate ($3 - 4 \times 10^{-3}$ yr^{-1}; Cappellaro & Turatto 1997). This is in good agreement with the measured rates of SNe Iax (31^{+17}_{-13} SNe Iax for every 100 SNe Ia in a given volume; Foley et al. 2012). The birthrate from $\alpha_{\rm ce}\lambda = 0.5$ is lower than that of $\alpha_{\rm ce}\lambda = 1.5$, since the post-CE binaries are more likely to be located in the SN Ia production region for $\alpha_{\rm ce}\lambda = 1.5$. As expected, these rates are consistent with the double-detonation model only producing part of the overall SN Ia rate (for a recent review of other potential SN Ia formation channels see Wang & Han 2012).

The delay times of SNe Ia are defined as the time interval between the star formation and SN explosion. The various progenitor models can be examined by comparing the delay time distributions with that of observations. Figure 4 displays the delay time distributions of SNe Ia for the double-detonation model. In the figure, we see that SN Ia explosions occur between $\approx$70 Myr and

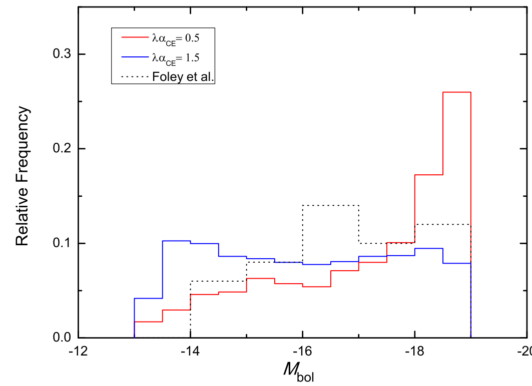

Figure 5. Distribution of peak bolometric magnitudes from the population model (for two different $\alpha_{\rm ce}\lambda$ values). The data are observed SN Iax V-band magnitudes from Foley et al. (2012), several of which are lower limits.

$\approx$710 Myr after the starburst, consistent with the current SNe Iax sample, all of which have originated in late-type – i.e., star-forming – galaxies.

3.2. *Luminosity distribution*

To quantify the relationship between the WD explosion mass ($M_{\rm WD}$) and the SN Ia peak bolometric magnitude ($M_{\rm bol}$), Ruiter et al. (2012) recently carried out a series of simulations for a range of WD masses based on 1D sub-Chandrasekhar mass pure detonation models, following the earlier similar calculations by Sim et al. (2010). We note that these simulations assumed a central detonation, with no specified triggering mechanism; we assume that their broad results are applicable to double-detonation events. The SN Ia peak brightness in their simulations is directly related to the WD explosion mass. We apply the $M_{\rm WD} - M_{\rm bol}$ relationship found by Ruiter et al. (2012) to derive the SN Ia peak brightness. The resulting luminosity distribution is plotted in Figure 5. There we also show observed peak V-band magnitudes from Foley et al. (2012), although several of those are lower limits and the sample is still probably too small to draw strong conclusions from the shape of the distribution. Nonetheless, the predicted peak magnitude range reproduces the full observed diversity of SNe Iax ($-14.2 \gtrsim M_{\rm V} \gtrsim -18.9$ mag; Foley et al. 2012). The predicted range ($-13 \gtrsim M_{\rm bol} \gtrsim -19$ mag) does add a tail stretching to fainter magnitudes, which might indicate a deficiency in the models or an observational bias against discovering the fainter SNe Iax.

4. DISCUSSION AND CONCLUSIONS

The most relevant known system to our current work is perhaps CD$-$30 11223, which has been identified as a CO WD + sdB star system with a $\sim$1.2 h orbital period (Geier et al. 2012; Vennes et al. 2012). Due to the short orbital period, angular momentum loss from GWR is large. After about 25 million years, the sdB star will begin to fill its Roche lobe while it is still in the He-core burning stage. CD$-$30 11223 may explode as an SN Iax via the double-detonation model in the future evolution. Other known CO WD + He-donor systems (e.g., KPD

1930+2752, V445 Pup, and HD 49798 with its WD companion) may produce SNe Ia via other progenitor models (see Wang & Han 2012).

The surviving companions from the model presented here for SNe Iax may also explain hypervelocity helium-rich stars like US 708 (e.g., Hirsch et al. 2005) due to the short orbital periods at the moment of SN explosion (see also Justham et al. 2009; Wang et al. 2009). Studying such high-velocity helium-rich stars (and their WD descendants) might provide a way to test this model.

In this Letter, we have systematically studied a helium double-detonation model for SNe Iax in which the donor star is non-degenerate. (1) This model can naturally produce SN explosions with helium lines and without hydrogen lines. (2) The event rate agrees with the inferred rates of SNe Iax. (3) The explosions in this model occur between $\approx$70 Myr and $\approx$710 Myr after the starburst, i.e., in relatively young stellar populations, consistent with the host galaxy morphologies of known SNe Iax. (4) By adopting an existing relationship between CO mass and SN luminosity for pure detonations, we find a SN luminosity range from -13 mag to -19 mag, which compares well to the current diversity of SNe Iax ($-14.2 \gtrsim M_{\rm V} \gtrsim -18.9$ mag). The overall population properties resulting from this model therefore seem promisingly consistent with the known collection of SNe Iax.

Confirmation that helium double-detonation explosions can produce a form of SN Ia would finally answer a fascinating astrophysical question, and help to constrain our understanding of explosion physics. However, our results suggest a new problem: why would systems with non-degenerate helium donors make SNe Iax but not – or only rarely – those with He WD donors? Degenerate donors tend to produce higher mass-transfer rates than our non-degenerate donors (see, e.g., Han & Webbink 1999), and higher mass-transfer rates require less massive helium layers for ignition (see, e.g., Shen & Bildsten 2009). So perhaps helium layer detonations in systems with degenerate donors typically involve helium layers which are not massive enough lead to a double-detonation? Alternatively, if double-detonations are triggered in systems with lower-mass helium layers then perhaps the explosion properties are not sufficiently altered for them to be identified as peculiar? We intend to study this in future by adopting more sophisticated assumptions about the properties of the helium layer at ignition. The 2002cx-like subclass of SNe Ia certainly deserves further detailed study.

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